ROTOR POSITION ESTIMATION FOR LOW SPEED AND STANDSTILL OPERATIONS IN MULTIPHASE PMSMs WITH NON-SALIENT POLES

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***Abstract* – A rotor position estimation for low speed and standstill applications in multiphase PMSMs with non-salient poles is presented in this paper. For this purpose, a comprehensive state of the art was performed. Then, an estimation method was proposed based on existing methods for surface three-phase PMSMs, and is finally adapted to a five-phase machine. Experimental results are illustrated and analysed.**

I. INTRODUCTION

The elimination of the rotor position detection sensor for high-performance vector control of PMSM drives remains to this day a crucial challenge for the integration of multiphase PMSMs in embedded applications such as electric vehicles. Multiphase machines are good candidates for electric mobility because of their functional reliability and their ability to operate at high power with low voltage, given that the required power per-phase rating of the multiphase inverter is reduced [1]. More recently, with the use of smaller large-gap components such as GaN transistors, a higher number of phases will allow better use of available space. The study of sensorless control in multiphase machines [5] is nonetheless rather new and much work remains ahead.

Two main challenges were identified for sensorless control of a multiphase PMSM with non-salient poles. The first one deals with the issue that the classical model-based sensorless position detection methods [1], have a poor performance at low and zero rotor speed. For this reason, many specific models are created to operate at low speed. Amongst these, High Frequency (HF) signal injection methods (including sinusoidal wave, rotating voltage, square wave injection and pulse injection) [3], are the most commonly used. As a second issue, it was established that the case of non-salient pole machines has the particularity of having very similar *d*- and *q*-axes impedances in the decoupled frame. This invalidates most of the classical methods for position detection at low speed, because they are based on the utilization of the reluctance effect due to saliencies in IPMSM's rotors. Solutions to this challenge are less numerous. One of them [2] includes a variation of a classical HF signal injection method, and is adapted and used in this work.

This paper proposes therefore the design of a position estimation method, based on [2], which is implemented and tested for a five phase non-salient pole PMSM. The machine model and methodology are detailed in Section II. Section III will present the practical results obtained and a brief analysis and discussion to how this method may be used in closed-loop and for the secondary fictitious machine. Conclusions and future work are presented in Section IV.

II. DESIGN OF POSITION ESTIMATION METHOD FOR NON-SALIENT POLE FIVE-PHASE PMSM

A. HF d-q model of a low saliency five-phase PMSM

A five-phase PMSM, can be decoupled into two fictitious independent two-phase machines defined by the projection in the planes $(\mathbf{x}_\alpha, \mathbf{x}_\beta)$ and $(\mathbf{x}_x, \mathbf{x}_y)$, and a one-dimensional homopolar machine defined by the projection in the line eigenvector $\mathbf{x}_h$. This is achieved with the Concordia transformation. In this case, the main machine (*α-β* frame) interacts with the first harmonics, and the secondary machine (*x-y* frame), with the third ones. Applying a Park transformation, the electrical equations for the primary machine in the d_1-q_1 rotating frame are expressed by, [4]

$$\begin{bmatrix}V_{d1}\\ V_{q1}\end{bmatrix}=\begin{bmatrix}R+sL_{d1} & -\omega_e L_{q1}\\ \omega_e L_{d1} & R+sL_{q1}\end{bmatrix}\begin{bmatrix}i_{d1}\\ i_{q1}\end{bmatrix}+\begin{bmatrix}0\\ \omega_e\sqrt{\frac{5}{2}}\Phi\end{bmatrix} \qquad (1)$$

$R + sL_x$ can also be noted as Z_x, the phase impedance in the decoupled frame. The HF machine model of a low saliency PMSM in the very low-speed region can be described by, [2]

$$\begin{bmatrix}V_{d1,h}\\ V_{q1,h}\end{bmatrix}=\begin{bmatrix}Z_{d1,h} & 0\\ 0 & Z_{q1,h}\end{bmatrix}\begin{bmatrix}i_{d1,h}\\ i_{q1,h}\end{bmatrix} \qquad (2)$$

Given the symmetry of the *d*- and *q*- axis when there are no significant saliencies in the rotor, in (2) $Z_{d1,h} \approx Z_{q1,h} \approx Z_{dq1,h}$. This equation is identical when considering the secondary fictitious machine, but in d_3-q_3 frame.

B. HF square wave injection and rotor position estimation utilizing square wave injection and envelope sensing

The method consists of identifying the angle of an estimated synchronous frame *δ-γ*, $\hat{\theta}_{re}$, by injecting a square wave in this estimated reference frame and measuring the high-frequency component of the projection in the stationary frame α-β. The actual rotor angle $\theta_{re} = \hat{\theta}_{re} - \Delta\theta$, may be found by implementing closed-loop control and correcting for Δθ. This is better viewed in Figure 1.

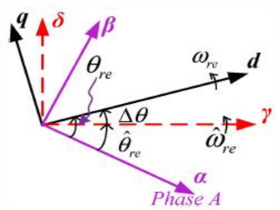

Fig 1. *α-β* stationary frame, d_1-q_1 rotating frame, *δ-γ* estimated frame [2]

The injected square signal is as expressed in (3), with V_h being the magnitude of the injected HF voltage, $v_{\gamma\delta,h}$ the voltage components, and *n= 1, 2, 3, ..., etc*.

$$\begin{bmatrix} v_{\gamma,h} \\ v_{\delta,h} \end{bmatrix} = V_h \begin{bmatrix} (-1)^n \\ 0 \end{bmatrix} \tag{3}$$

It can be proven [2] that by detecting the envelopes of the HF current components in the stationary reference frame ($\tilde{i}_{\alpha\beta,h}$), the estimated rotor position can be extracted as in (4)

$$\begin{cases} \tilde{i}_{\alpha,h} = -\dfrac{V_h}{Z_{dq,h}} \cos\left(\hat{\theta}_{est}\right) \\ \tilde{i}_{\beta,h} = +\dfrac{V_h}{Z_{dq,h}} \sin\left(\hat{\theta}_{est}\right) \end{cases} ; \hat{\theta}_{est} = -\tan^{-1}\left(\dfrac{\tilde{i}_{\beta,h}}{\tilde{i}_{\alpha,h}}\right) \tag{4}$$

C. Quadrant selection and quadrant adapted responses

Given the nature of the calculation of the *atan* function, an additional step to determine the quadrant of the angle becomes necessary. For this purpose, a quadrant selection method is proposed. This method assumes that a torque reference can be given to the machine, even at zero speed, and the polarity of the machine can be detected from the low-frequency component of currents i_α and i_β (if no measurable torque can be created, alternative methods, such as the CORDIC method [1] may be explored). The block diagram of the complete estimator is shown in Fig. 2.

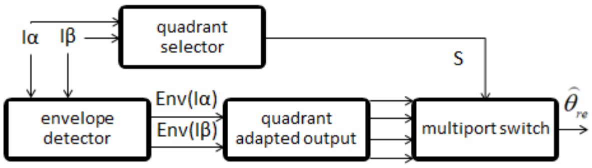

Fig. 2. Block diagram of the proposed position estimation method

The quadrant of the rotor is therefore determined by the sign of the low frequency component of i_α, i_β as in Table I.

TABLE I. DETERMINATION OF QUADRANT ADAPTED OUTPUT

iα	*iβ*	Quadrant	S	Quadrant adapted output*: atan (θ_{est})*
>0	>0	1st	4	env(i_β)/ env(i_α)
>0	<0	2nd	3	env(i_β)/ -env(i_α)+π
<0	<0	3rd	1	-env(i_β)/-env(i_α)+π
<0	>0	4th	2	-env(i_β)/env(i_α)+2π

III. EXPERIMENTAL RESULTS

The method was tested for a five-phase machine (open-loop at this time) through the dSPACE1006 board. Position estimation and estimation error for different speeds are shown in Fig. 3 and Fig. 4, respectively. It can be observed that the proposed method yields a fair estimate of the position whenever there is a torque reference in the *d-q* axis. The estimation error is highly sensitive to the rotational speed of the rotor. At low speed (e.g. 50 rpm) the method yields a maximum error of about 8°. In order to use this method for real time control of the machine, a closed loop control should be implemented in order to have the estimation to converge to the actual rotor angle.

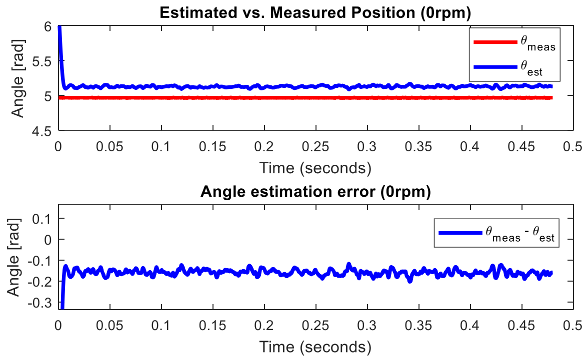

Fig. 3. Estimated and measured angle (top figure) and error in electrical angle (bottom figure) at standstill (0 rpm)

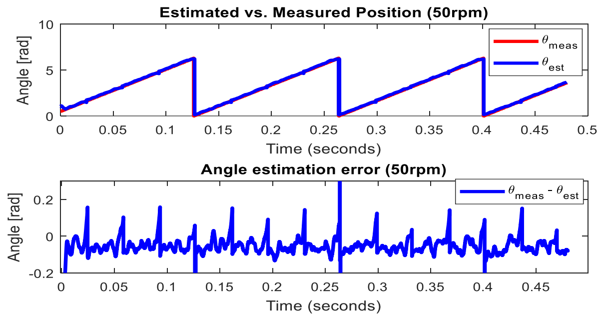

Fig. 4. Estimated and measured angle (top figure) and error in electrical angle (bottom figure) at 50 rpm

The possibility to use the fictitious secondary machine for position detection is an advantage when compared to three phase machines, as the method will not interfere significantly with the torque production mechanism of the primary machine. It is possible to do so, by calculating the rotor speed from the estimated angle (which will be three times), and deducing the position from this calculation.

IV. CONCLUSIONS AND WORKAHEAD

A rotor position estimation method for low speed applications in multiphase PMSMs with non-salient poles is designed and tested. The results show a fair detection. An analysis was performed and proposals were made to improve the obtained results and adapt the method to the secondary fictitious machine. Work ahead will include the closed-loop detection and secondary machine implementation.

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